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EVALUATION OF EDDY CURRENT – INDUCED MAGNETIC FIELDS

by
Lennard J. Wolfson

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FOREWORD

This publication is a final technical report on NAVEODFAC technical project non-magnetic/non-conductive tools. It describes work performed by the NAVEODFAC during the period July 1972 to January 1973 to evaluate and develop design procedures for the selection of materials for low magnetic signature tools.

TABLE OF CONTENTS

APPENDICES

LIST OF ILLUSTRATIONS

ABSTRACT

Using a simple theoretical approach, a method has been formulated to determine the eddy current-induced magnetic fields (ECI magnetic fields) produced by metallic objects moved in the Earth's magnetic field. The method permits the calculation of the ECI magnetic field of objects having simple shapes and, with a little ingenuity, can be readily extended to more complex shapes. The basic theory establishes criteria by which materials can be selected and designs evaluated to yield a minimum ECI magnetic field.

INTRODUCTION

With the advent of sophisticated fuzing, increasing difficulty has been encountered in the neutralization and disposal of live ordnance. One type of fuze, used in mines and other types of ordnance, functions in response to changes in the local magnetic field. Once energized, the fuze adjusts itself so that the local environmental magnetic field, due to the Earth's field and any perturbating objects in its vicinity, is established as a reference. Any disturbance in this reference magnetic field will result in activation of the fuze and the initiation of the ordnance item.

In order to neutralize and dispose of ordnance with this general type of fuzing, a strict limitation on the magnetic properties of materials and tools to be used must be established. Such a standard is presented in the form of a specification titled: "Magnetic Influence Limits for Non-Magnetic Equipment Used in the Proximity of Magnetic Influence Ordnance," MIL-M-19595B. This specification deals with two basic areas: the static magnetic effect and the eddy current generated field effect. Limiting maximum field disturbance values of 5 gamma are set forth for each effect and also for the summed total of the two effects.

The static magnetic effect involves the evaluation of the magnetic field disturbance obtained when an object is brought from infinity to a 4.5-inch distance from a sensor alined with the Earth's magnetic field. The disturbance is measured with respect to the reference field. This measurement is done for each of the three orthogonal axes of the sample with the largest total fluctuation being compared to the limiting value presented in the specification. The limiting value of 5 gamma is an extremely small magnetic field disturbance, as can be seen when it is compared to the Earth's magnetic field which has a value of approximately 50,000 gamma. Thus, a fluctuation in the field of one part in 10,000 is sufficient to fail a sample.

Evaluation of materials to pass this part of the specification entails selecting materials having permeabilities very close to 1.000. This criteria is satisfied by most common alloys of aluminum, copper, and magnesium, as well as by other materials such as leads and some stainless steels; SS 310 in particular. The only difficulty arises in maintaining the quality control in the manufacturing of the parts to be used, to be sure that no ferrous impurities are accidently added and that no magnetic changes are introduced during cold working and other fabricating processes.

The second portion of the specification deals with eddy current magnetic fields. It is a relatively new addition to the specification and has not been analyzed in any detail. The only design procedure in use is to fabricate tools and equipment and test the finished item to see if it passes the specification. This report attempts to rectify this lack of information and tries to establish equations to evaluate the phenomena and to use in the design of tools and hardware when eddy current generated fields are of concern.

The eddy current generated field effect concerns itself with the magnetic field produced by an object that is moving in a magnetic field. As a conductor is moved through a magnetic field, a quantity of magnetic flux passes through it. If the amount of flux is changed, currents are induced. These currents, in turn produce their own magnetic fields. Thus, a moving conductor, whether in the form of a loop of wire as in a motor or generator, or as any solid shape has induced currents, eddy currents, and their associated induced magnetic fields.

In the case of ordnance fuzes, the initial magnetic field is the Earth's (including local perturbations) and is on a local scale steady and uniform. Thus, the problem becomes a determination of the eddy current induced magnetic fields produced by flux changes due to the motions of the sample. The specification prescribes the manner of measurement and the limitation for the disturbance.

The recommended measurement proceeds as follows: The detector is alined perpendicular to the Earth's field and the sample is brought to within 4 1/2 inches of the detector, its reference axis perpendicular to the field and into the detector. The sample is then rotated, about an axis through its midpoint, through an angle of 30 degrees ($\pm$ 15 degrees) in the direction of the sensor. The rate of motion is such that 15 complete rocking motions occur in 10 seconds. This is equivalent to 15 rpm. The same procedure is repeated for each of three perpendicular axis and the value for the eddy current effect is the maximum disturbance observed. That is, the sum of the absolute values of the plus and minus field fluctuations. Again, as in the static magnetic effect, the maximum permissible field is 5 gamma, which allows a maximum fluctuation of only one part in 10,000 in the reference field seen by the sensor. In order to satisfy this limitation, the redesign of many of the existing disposal tools is necessary.

To aid in this procedure, by creating an engineering design base for the evaluation of materials and for the design of nonmagnetic tools and equipment, a very simplified theoretical formulation of the eddy current phenomenon was determined. Test results were generated which verify the formulation and establish a solid base for evaluating graphically and mathematically the ECI magnetic fields.

These results are summarized in a series of graphs containing over 150 data points from varied test samples. The graphs relate a theoretical variable to the actual ECI magnetic field measured for that particular sample. The variable used to determine the ECI magnetic field is only a function of the samples dimensions, a, b & t, the distance from the sample R, and the resistivity, ρ (which is readily obtainable from any materials handbook). The relationship obtained, $H = (18000)\ F_i(a,b,R)$, is satisfied by flat plates of all dimensions and materials, and also, applies to the evaluation of cylindrical objects, tools, and other samples of more complex shapes.

In addition, a listing of the common alloys of aluminum, copper, magnesium, and other materials with low permeabilities has been compiled according to resistivity. This presents a simple basis for material selection and when used in conjunction with general design procedures, offers a complete basis for the design of nonmagnetic tools and equipment in regard to ECI magnetic fields.

TECHNOLOGY

The approach taken to evaluate the ECI magnetic fields of flat plates, was to assume that the eddy currents take a form similar in shape to the form of the plate under consideration. Thus, a circular plate would have circular eddy currents and a rectangular plate would have rectangular eddy currents. Using this approach, the ECI magnetic field generated by a loop having each of these two shapes was calculated for movement in a uniform magnetic field in accordance with specifications.

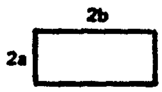
The magnetic field produced by a current carrying loop of conducting material is found by the general equation:

$$H = \frac{1}{4\pi \epsilon_0 C^2} \int_l \frac{I}{r^2}\, dl$$

For a rectangular loop, the integral reduces to:

$$H = \frac{Iab}{\pi \epsilon_0 C^2} \left[\frac{1}{\sqrt{R^2+a^2+b^2}}\right] \left[\frac{1}{R^2+a^2} + \frac{1}{R^2+b^2}\right]$$

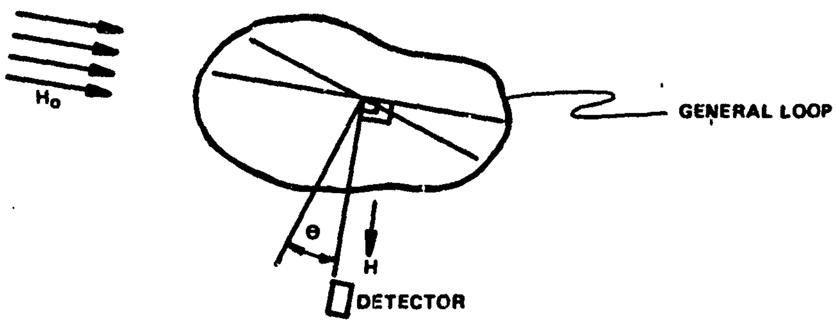
Where a and b are as shown



For a circular loop of radius a, the integral reduces to:

$$H = \frac{I}{2\epsilon_0 C^2} \left[\frac{a^2}{(a^2+R^2)^{3/2}}\right]$$

It is now necessary to evaluate the current I. Starting with an appropriate coordinate system, the equations will be developed. For a generalized loop:



$$\text{Magnetic flux into loop} = \phi_H = H_0 A \sin \Theta$$

where, A = enclosed area of loop

The electric emf generated in the loop is then:

$$E = \frac{-d\phi_H}{dt} = H_0 A \cos\Theta \frac{d\Theta}{dt}$$

The current is:

$$I = \frac{E}{R} = \frac{H_0 A \cos\Theta \, d\Theta/dt}{\rho\left(\frac{L}{A_l}\right)}$$

where, L = length of perimeter of loop
A_l = cross sectional area of loop conductor

The minimum and miximum values of I occur at $\Theta = O$. When motion is in one direction $\frac{d\Theta}{dt}$ is positive and I = I max. and when motion is in the opposite direction $\frac{d\Theta}{dt}$ is negative and I = I min. = -I max.

thus, $I\ max. = \left| I\ min. \right| = \frac{H_0 A \, d\Theta/dt}{\rho (L/A_l)}$

A and L will now be substituted to obtain the current for each loop form.

Circular Loop $\quad I\ max. = \frac{H_0 (\pi a^2)\, d\Theta/dt}{\rho\left(\frac{2\pi a}{A_l}\right)} = \frac{H_0\, a\, A_l\, d\Theta/dt}{2\rho}$

Rectangular Loop $\quad I\ max. = \frac{H_0 (4ab)\, d\Theta/dt}{\rho \frac{(4(a+b))}{A_l}} = \frac{H_0\, ab\, d\Theta/dt\, A_l}{\rho (a+b)}$

where, ρ = resistivity

The specification requires $\left|\frac{d\Theta}{dt}\right| = \frac{\pi}{2}$. Substituting this into the equations for I and then substituting the appropriate I into the field for the loop, the following equations are obtained.

Circular Loop $\quad H = \frac{\pi}{2\epsilon_0 C^2} \left[\frac{H_0 A_l}{4\rho}\right] \left[\frac{a^3}{(a^2+R^2)^{3/2}}\right]$

Rectangular Loop $\quad H = \frac{\pi}{2\epsilon_0 C^2} \left[\frac{H_0 A_l a^2 b^2}{\pi \rho (a+b)}\right] \left[\frac{1}{\sqrt{R^2+a^2+b^2}}\right] \left[\frac{1}{R^2+a^2} + \frac{1}{R^2+b^2}\right]$

The total disturbance with respect to the reference field of the sensor is 2H for each case due to the positive and negative sign change of $\frac{\pi}{2}$.

The equation can then be written:

Rectangular Loop $$H = K_o \left(\frac{A_l}{\rho}\right) \left[\frac{a^2 b^2}{\pi(a+b)}\right] \left[\frac{1}{\sqrt{R^2+a^2+b^2}}\right] \left[\frac{1}{R^2+a^2} + \frac{1}{R^2+b^2}\right] = K_o \left(\frac{A_l}{\rho}\right) f(a,b,R)$$

Circular Loop $$H = K_o \left(\frac{A_l}{\rho}\right) \left[\frac{a^3}{4(a^2+R^2)^{3/2}}\right] = K_o \left(\frac{A_l}{\rho}\right) g(a,R)$$

The total fields of all the eddy currents in a plate were now assumed to be approximated by a loop having one half of the overall dimensions of the plate.

Rectangular Plate $$H = K_1 \left(\frac{A_l}{\rho}\right) f\left(\frac{a}{2},\frac{b}{2},R\right)$$

Circular Plate $$H = K_2 \left(\frac{A_l}{\rho}\right) g\left(\frac{a}{2},R\right)$$

It is now necessary to evaluate the cross sectional area of the current flow, A_l. For a circular plate it is assumed to be radius times thickness, (at), and for a rectangular plate it is assumed to be the average width times the thickness, $\left(\frac{a+b}{2}\right)(t)$. Substituting, a final form for the equations is derived.

Rectangular Plate $$H = K_3 \left[\left(\frac{a+b}{2}\right)\left(\frac{t}{\rho}\right) f\left(\frac{a}{2},\frac{b}{2},R\right)\right]$$

Circular Plate $$H = K_4 \left[a\left(\frac{t}{\rho}\right) g\left(\frac{a}{2},R\right)\right]$$

Using these two approximations, various metallic samples ranging from aluminum foil 0.001-inch thick and 18 inches by 13 3/4 inches in dimension to a lead block 1-inch thick and 3 inches by 6.2 inches in dimension were evaluated. The results are presented in Appendix A and Figures 1 and 2.

The ECI magnetic field of each sample was measured with a magnetometer while the sample was moved in accordance with the military specification. A special apparatus permitted repeatable motion at the specified rate and angular variation. A strip chart recorder was used to obtain a permanent record of the fields generated by each sample (Figure 3). The Earth's magnetic field was measured prior to each series of measurements and the results were normalized to H_o = 500millioersteds = 50000γ. Data were obtained for sample to probe distances, R, of 2.5 inches, 4.5 inches, and 6.7 inches.

The magnetometer was calibrated using a long solenoid which served as a standard known magnetic field. The solenoid also permitted the calibration of the magnetometer at a frequency of 1.5 Hz which corresponds to the field oscillation obtained by the movements required in the specification, MIL-M-19595B (see Appendix E).

An additional correction to the equations was found necessary. This correction was made to account for the assumed variation in the shape of the eddy currents as the plate becomes more and more elongated. Figure 4 illustrates the effect.

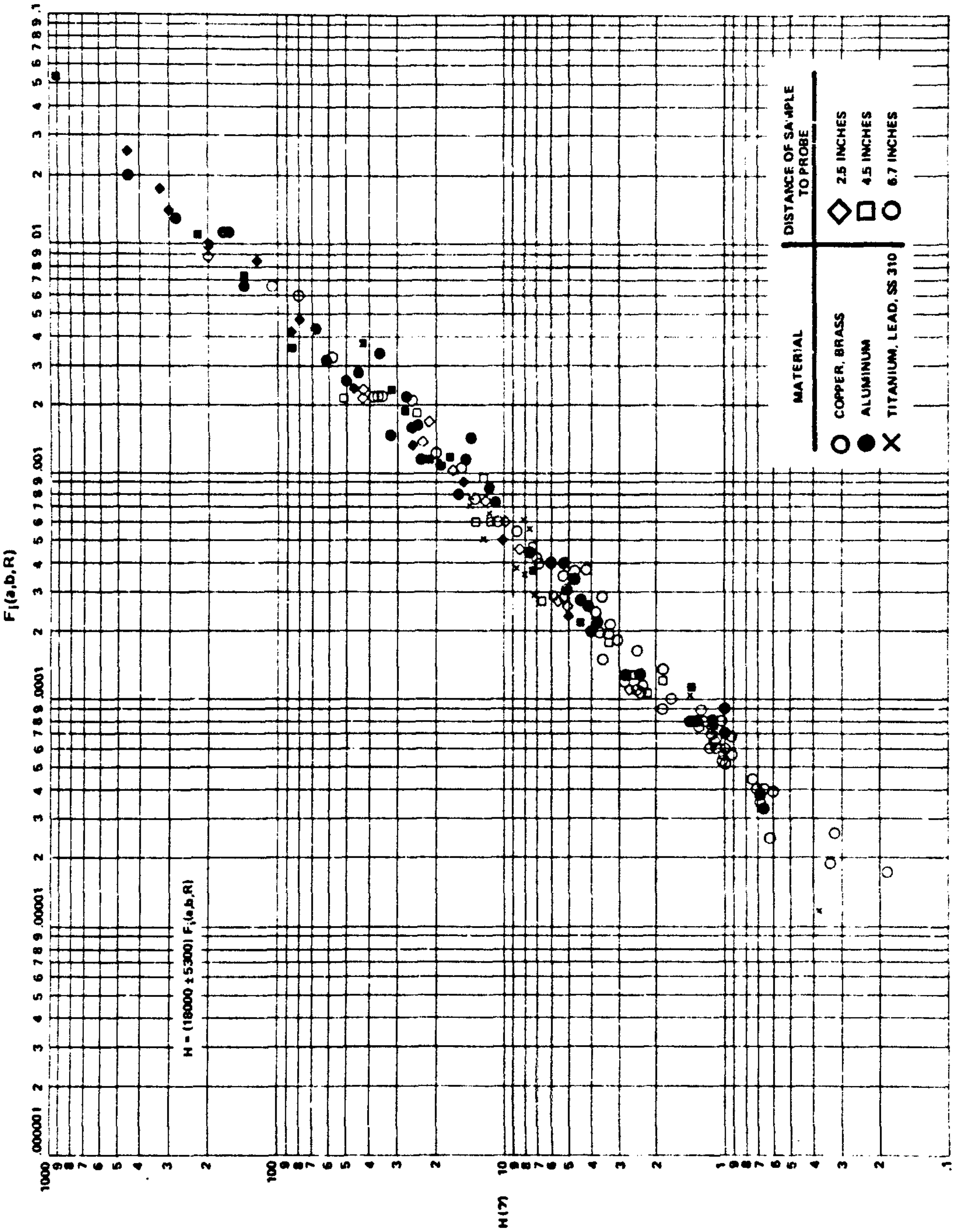


Figure 1. Measured ECI Magnetic Field as a Function of $F_i(a,b,R)$ (Flat Plates).

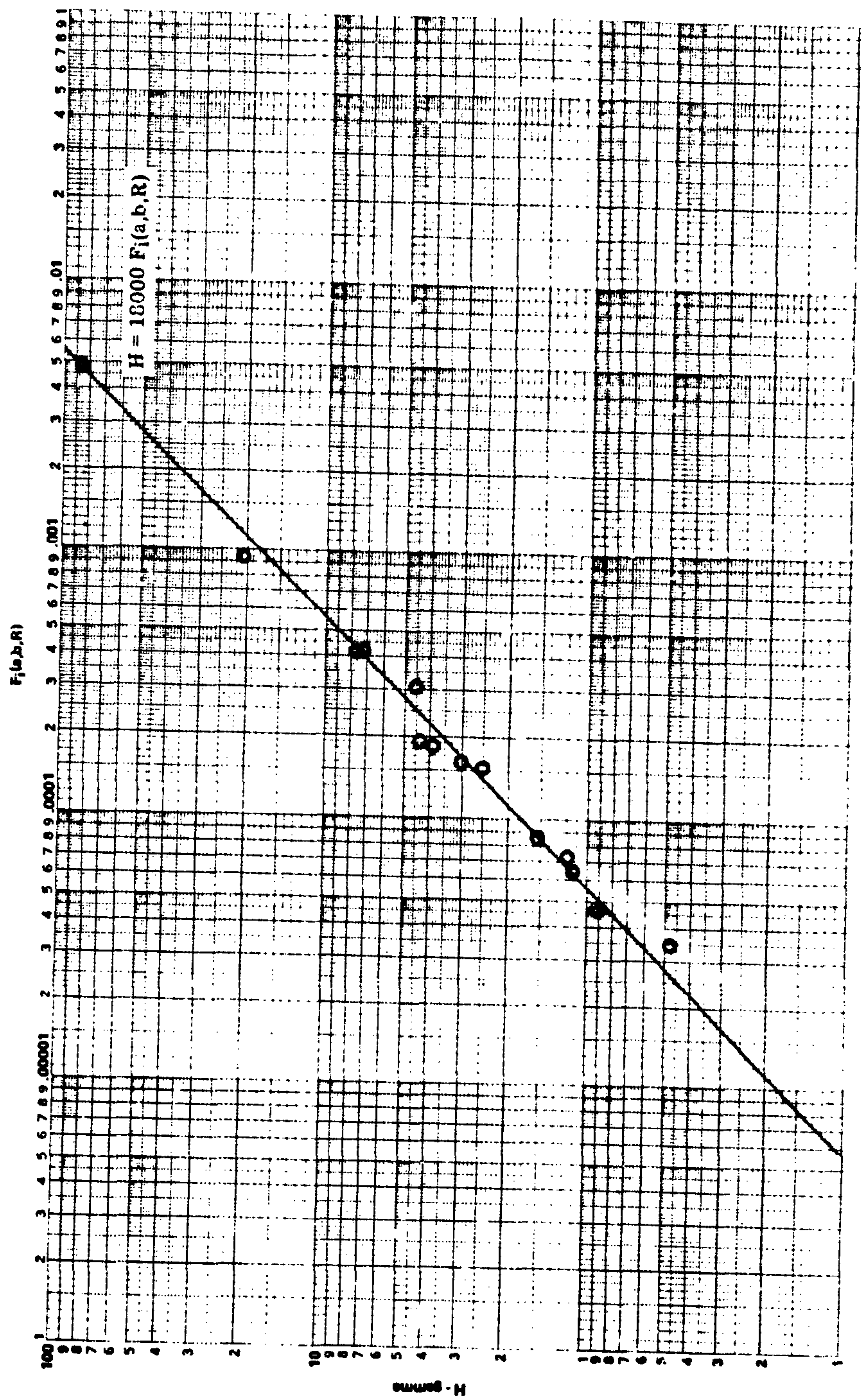
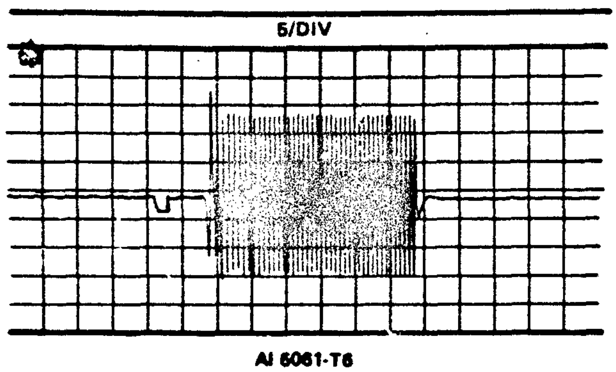


Figure 2. Measured ECI Magnetic Field as a Function of F_i(a,b,R) (Pipes and Solid Cylinders).



Vertical Scale:	**5 gamma/div**
Horizontal Scale:	**5 sec/div**
Sample:	**Al 6061-T6** **(12 1/8 inches x 12 inches x 0.355 inch)**

Figure 3. Typical Strip Chart Trace.

Figure 4. Hypothesized Eddy Current for Elongated Shapes.

The following was empirically established as a correction:

for, $\frac{b}{a} > 2 \qquad H = K_3 \left[\left(\frac{a+b}{2}\right)\left(\frac{t}{\rho}\right) f\left(\frac{a}{2},\frac{b}{2},R\right)\right]\left(\frac{2}{b/a}\right) =$

$\frac{b}{a} < 2 \qquad H = K_3 \left[\left(\frac{a+b}{2}\right)\left(\frac{t}{\rho}\right) f\left(\frac{a}{2},\frac{b}{2},R\right)\right]$

Figure 5 shows how this correction makes the fields obtained from the elongated plates conform to the relationship found for less elongated shapes. Although this is strictly an empirical correction, it appears to give the desired result over a wide range of samples and is assumed to be valid for the formulation.

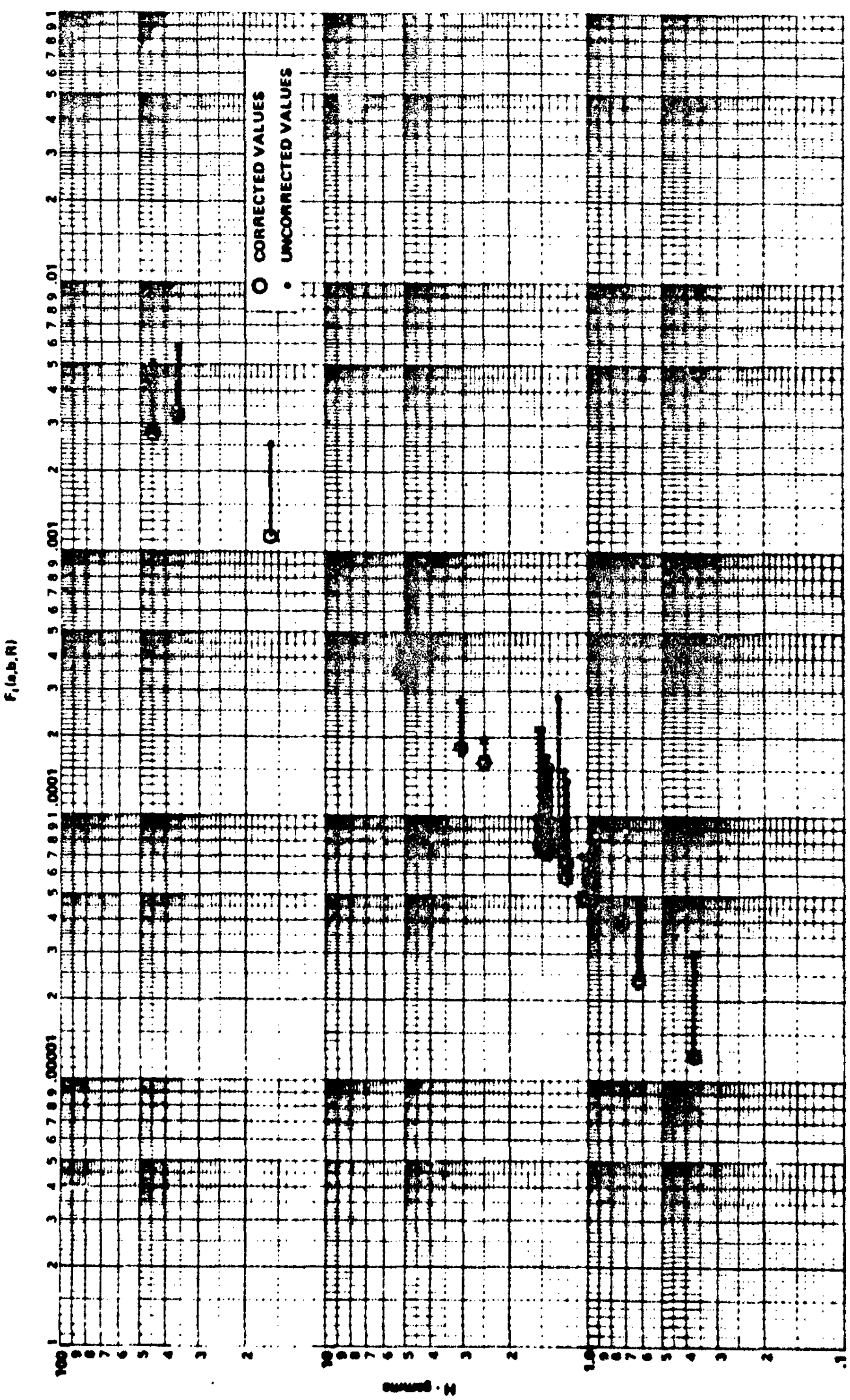
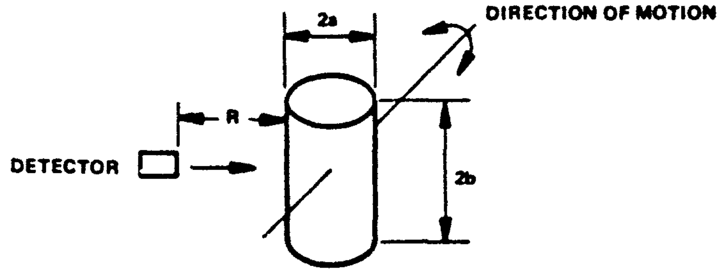


Figure 5. Configuration Factor Correction for Elongated Plates.

The investigation of pipes, solid circular cylinders, irregular shapes, and fields not at the center of a sample has yielded consistent results, although large numbers of samples were not tested. The solid shaped objects can be made to conform to the same type of analysis as the flat plates. The appropriate equations are the following:

SOLID ROD

SIDE VIEW



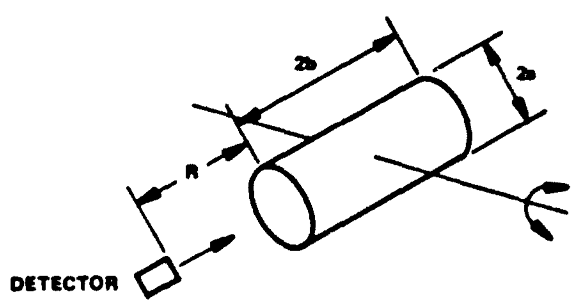
$$H = K_3 \left(\frac{a+b}{2}\right) \left(\frac{t_{eff}}{\rho}\right) \left[\frac{f(a/2,b/2,R_1) + f(a/2,b/2,R_2)}{2}\right]$$

where, $t_{eff} = \frac{\Pi a}{2}$

$R_1 = R + .067(2a)$

$R_2 = R + .933(2a)$

END VIEW



$$H = K_4 \left(\frac{a t_{eff}}{\rho}\right) \left[\frac{g\left(\frac{a}{2},R_1\right) + g\left(\frac{a}{2},R_2\right)}{2}\right]$$

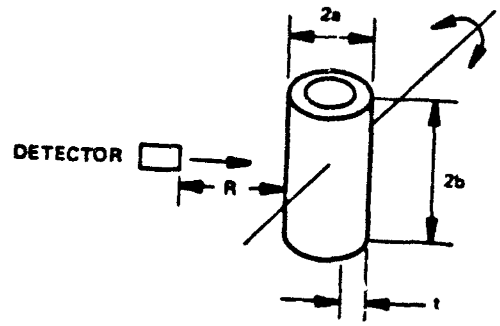
where, $t_{eff} = 2b$

$R_1 = R + \frac{1}{4}(2b)$

$R_2 = R + \frac{3}{4}(2b)$

PIPE

SIDE VIEW



$$H = K_3 \left(\frac{a+b}{2}\right) \left(\frac{t_{eff}}{\rho}\right) \left[\frac{f(a/2,b/2,R_1) + f(a/2,b/2,R_2)}{2}\right]$$

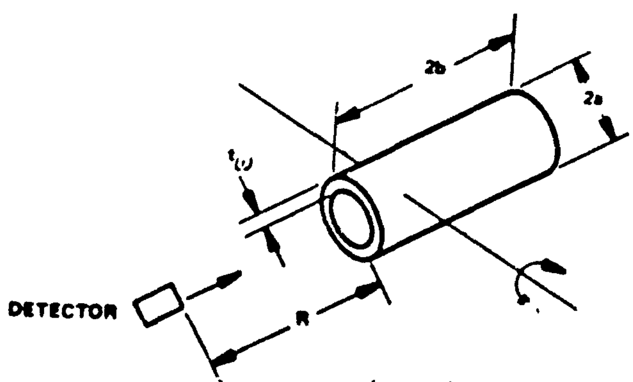
where, $t_{eff} = \frac{\pi}{4}\left(\frac{(2a)^2 - (2a-2t)^2}{2a}\right)$

t = wall thickness

$R_1 = R + .067(2a)$

$R_2 = R + .933(2a)$

END VIEW



$$H = K_4 \left(\frac{t_\omega t_{eff}}{2\rho}\right)\left(\frac{g(a,R_1) + g(a,R_2)}{2}\right)$$

where, $t_{eff} = 2b$

$R_1 = R + \frac{1}{4}(2b)$

$R_2 = R + \frac{3}{4}(2b)$

More complex shapes and forms can be analyzed with respect to these equations and those for the flat plates. In general, the object can be approximated by a flat plate or plates having a corrected thickness and a corrected distance from the point of field measurements. This is essentially how the equations for the cylinders and solid rods were obtained and the same procedure can be used for any complex shape.

Four examples will now be presented as illustrations of the use of the formulation to calculate the ECI magnetic field.

EXAMPLE 1

Material: Al 1100-H (ρ = 3.02 microhm-cm)
Shape: Plate
Dimensions: 9 inches x 6 inches x .0625 inch

$H_0 = 50000\gamma$

From graph or calculated: $f\left(\frac{a}{2},\frac{b}{2},R_0\right) = 0.01546$

$$H = m\,F_i(a,b,R) = m\left(\frac{a+b}{2}\right)\left(\frac{t}{\rho}\right)f\left(\frac{a}{2},\frac{b}{2},R_0\right) = m\left(\frac{4.5+3}{2}\right)\left(\frac{.0625}{3.02}\right)(.01546)$$

$$H = m(.00120) = 18000(.00120) = 21.6\gamma$$

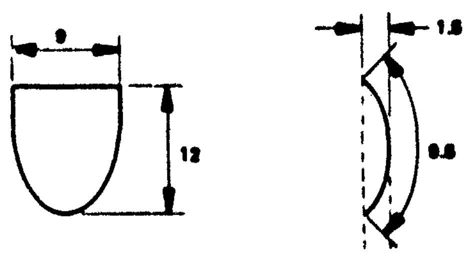
(Actual measured value $H = 22.1\gamma$)

EXAMPLE 2

Round pointed shovel

Material: Beryllium Copper (Cu 172) (ρ = 10.5 microhm-cm)

Shape:



Assume plate of dimensions 9 x 12 x .081 inch

$$t_{eff} = t\left(\frac{9.5}{9.0}\right) = .081\left(\frac{9.5}{9.0}\right) = 0.0855 \text{ (Curvature Correction)}$$

$$R = 4.5 + .75 = 5.25$$

$$f\left(\frac{a}{2},\frac{b}{2},R\right) = .02488$$

$$H = m\left(\frac{4.5 + 6}{2}\right)\left(\frac{.0855}{10.5}\right)(.02488) = m(.00106)$$

$$H = 18000(.00106) = 19.1\gamma$$

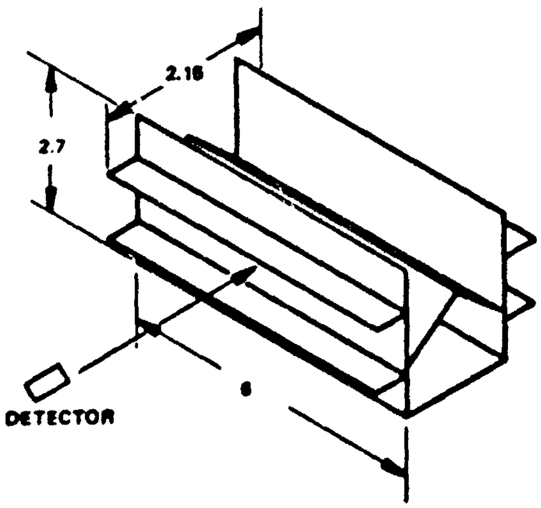
(Actual measured value H = 21γ)

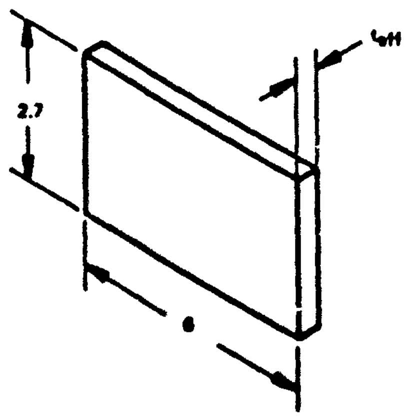
EXAMPLE 3

Mk 8 underwater shaped charge container

Material: Al 6063-T5 (ρ = 3.3 microhm-cm)
Dimensions: See Appendix D

Since the device is very complex but small in size the entire mass of the device will be averaged to a plate at the center line of the device.





An easy method to obtain t_{eff} is to weigh the object.

then, $$t_{eff} = \frac{\left(\frac{\text{Weight}}{\text{Density}}\right)}{(2a)(2b)} = \frac{\text{Weight (lbs)}}{(.098)\,(2.7)\,(6.0)} = \frac{.566\text{ lb}}{(.098)\,(2.7)\,(6.0)} = 0.3565$$

$2a = 2.7$ inches

$2b = 6$ inches

$R = 4.5 + 1.075 = 5.575$ inches

$$\text{Calculating } f\left(\frac{a}{2},\frac{b}{2},R\right) = 0.001593$$

$$H = m\left(\frac{1.35+3}{2}\right)\left(\frac{.3565}{3.3}\right)(.001593)\left(\frac{2}{3/1.35}\right) = m\,(.000337)$$

$$H = 18000\,(.000337) = 6.1\gamma$$

(Actual measured value $H = 6.0\gamma$)

EXAMPLE 4

Material: Brass 70-30 ($\rho = 6.16$ microhm-cm)
Shape: Plate
Dimensions: 12 inches x 6 inches x 0.125 inch

From graph or calculated: $f\left(\frac{a}{2},\frac{b}{2},R_o\right) = 0.0201$

$$H = m\left(\frac{6+3}{2}\right)\left(\frac{.125}{6.16}\right)(.0201) = m\,(.00183) = 18000\,(.00183) = 33\gamma$$

(Actual measured value $H = 24.6\gamma$)

Thus, excellent results are obtained for even the complex shaped charge container when using a simple approach and the derived formulation.

Figures 6 and 7 show how the ECI magnetic field changes with position relative to the center of a sample and with the addition of slots to a sample. These curves are the result of only a few test samples but they do show the type of variation in the ECI magnetic field to be expected.

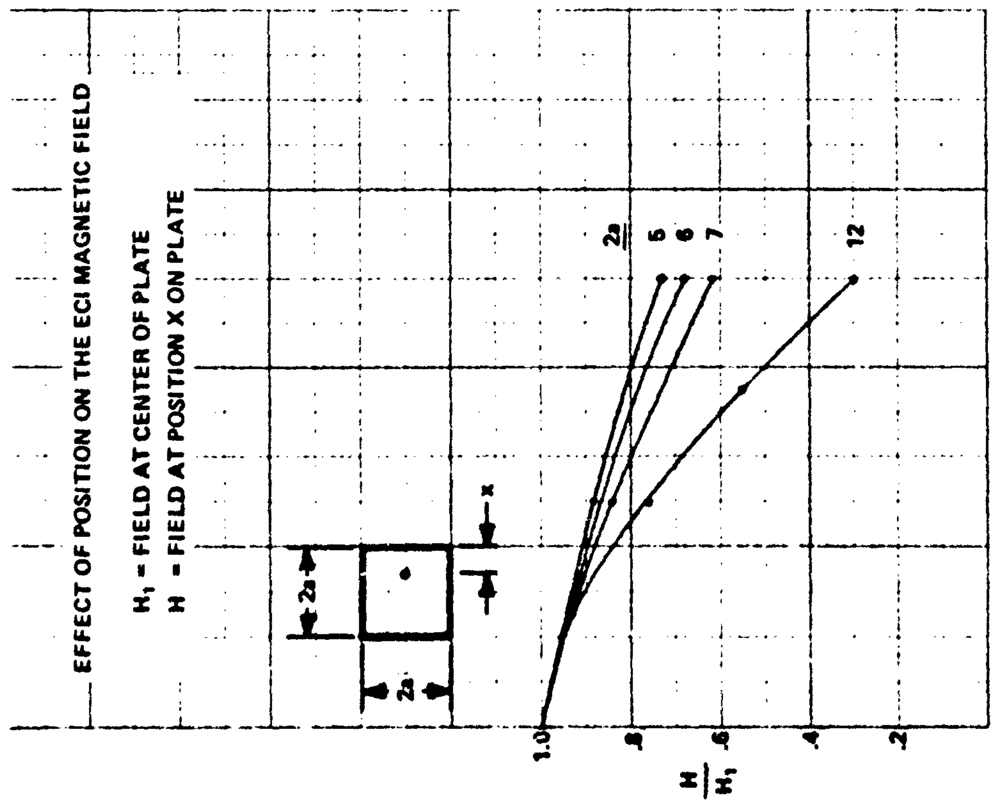


Figure 6. Effect of Position on the ECI Magnetic Field.

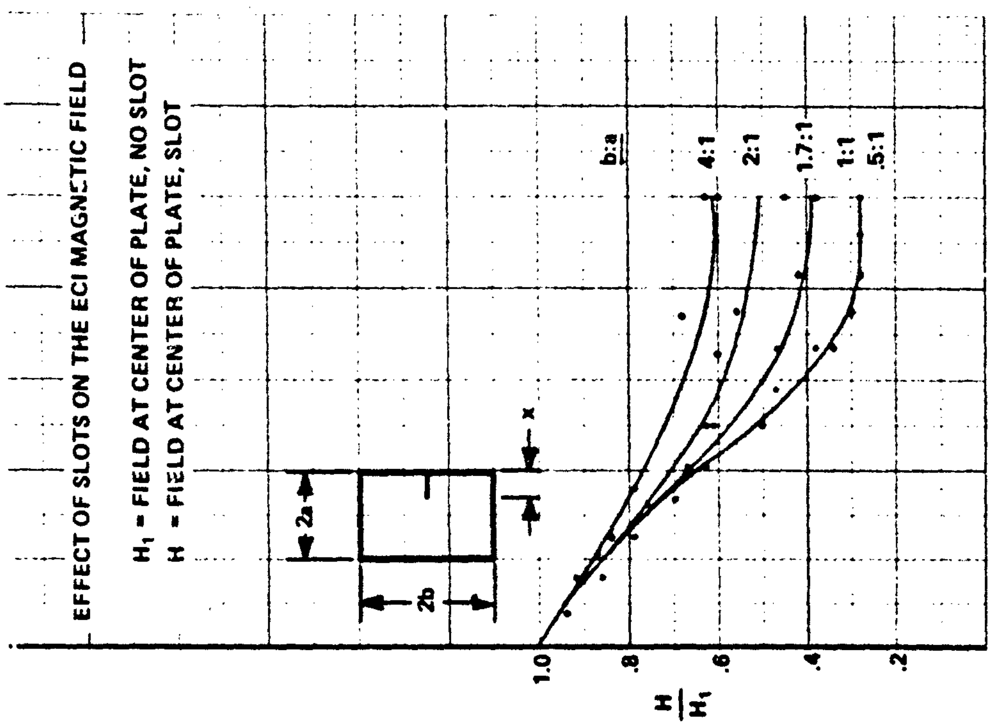


Figure 7. Effect of Slots on the ECI Magnetic Field.

CONCLUSION

The equations relating the resistivity and the dimensions of a sample to the ECI magnetic field can be summarized by the following equation.

$$H = m \boxed{F_i(a,b,R)} = (18000 \pm 5300)\ F_i(a,b,R)$$

The deviation in m corresponds to a 90 percent confidence level and although large in value, is consistent with the expected errors arising in the experimental measurements of the ECI magnetic field.

The function $F_i(a,b,R)$ corresponds to any of the functions describing plates, cylinders, rods, or more complex shapes. Thus, by calculating the appropriate $F_i(a,b,R)$ and then multiplying by 18000, the ECI magnetic field disturbance in units of gamma is obtained. A value of 4.5 inches must be chosen for R so that the requirements of the specification are satisfied.

General design criteria can also be obtained from the equation when it is written in a slightly different form.

$$H = (\text{Const})\left(\frac{t}{\rho}\right)$$

Thus, for any particular sample the ECI magnetic field is directly proportional to the samples thickness, t, and inversely proportional to the samples resistivity, ρ. The design of a tool or part to satisfy MIL-M-19595B or any other application where low eddy currents are desirable should then be directed toward selecting a material as thin as possible and as high in resistivity as possible.

An example of such a design selection will now be shown for an aluminum part. If the same part is fabricated from Al 1100 (ρ = 2.92 microhm-cm), Al 5052 (ρ = 4.93 microhm-cm), or Al 7075-T6 (ρ = 5.7 microhm-cm), the ECI magnetic field will be

Al 1100	H = 1.00
Al 5052	H = 0.59
Al 7075-T6	H = 0.51

when normalized to the ECI magnetic field of the Al 1100 part.

Thus, the selection of resistivity can yield the designer in this instance an approximate 50 percent reduction in the ECI magnetic field and even larger reductions, depending on the materials involved. (A listing of the resistivity of common alloys is presented in Appendix B.)

In addition, as a result of the varying strengths of different alloys, a part may be made thinner with a stronger alloy, and so, give a lower field disturbance. In context with this, the use of ribbing on thin materials will achieve the desired structural strength and will have lower magnetic fields than the same part manufactured in a solid form.

To simplify use of the formulation, a set of graphs of the functions $f\left(\frac{a}{2},\frac{b}{2},R_o\right)$ and $g(a/2,R_o)$ where $R_o = 4.5$ inches is included in Appendix C. These curves permit evaluation of flat plates and some complex objects without extensive calculations.

The problem of eddy current induced-fields can thus be calculated to a usable degree of accuracy. The formulation presents a systematic and comprehensive method by which designs and materials can be selected and analyzed prior to fabrication so as to save both time and effort in the design of low magnetic signature tools and equipment.

APPENDIX A

METALLIC SAMPLES

APPENDIX A

METALLIC SAMPLES

Sample No.	Form	Material	Thickness (inches)	Dimensions (inches)	ρ Resistivity ($\mu\Omega$-cm)	R (inches)	$f\left(\frac{a}{2},\frac{b}{2},R\right)$	$F_i(a,b,R)$	H (gamms)	$\frac{H}{F}$
1	Plate	Cu	.021	4 x 4	1.71	2.5	.01529	.000375	8.5	22643
2		Al6061-T6	.032		4.2			.000233	5.1	21888
3		Br 464	.026		6.63			.000120	2.8	23333
4		Br 464	.061		6.63			.000202	5.2	18440
5		Cu	.021	5 x 5	1.71		.02599	.000798	14.5	18170
6		Al6061-T6	.032		4.2			.000495	10.2	20606
7		Br 464	.026		6.63			.000254	5.2	20972
8		Br 464	.061		6.63			.000597	10.6	17755
9		Cu	.021	6 x 6	1.71		.03855	.00142	24.6	17324
10		Al6061-T6	.032		4.2			.000881	16.3	18502
11		Br 464	.026		6.63			.00454	8.6	18943
12		Br 464	.061		6.63			.00106	17.1	16132
13		Br 70-30	.125		6.16			.00235	93	18298
14		Cu (hard)	.135		1.77			.00882	202	22902
15		Al1100-H	.0625		3.02			.00239	48	20084
16		Al1100-H	.125		3.02			.00479	80	16701

METALLIC SAMPLES (Continued)

Sample No.	Form	Material	Thickness (inches)	Dimensions (inches)	ρ Resistivity ($\mu\Omega$-cm)	R (inches)	$f\left(\frac{a}{2},\frac{b}{2},R\right)$	$F_i(a,b,R)$	H (gamma)	$\frac{H}{F}$
17	Plate	Al1100-H	.375	6 x 6	3.02	2.5	.03855	.0144	300	20833
18	↓	Cu	.021	7 x 7	1.71	↓	.05207	.00224	43.6	19464
19	↓	Al6061-T6	.032	↓	4.2	↓	↓	.00139	26.9	19353
20	↓	Br 464	.026	↓	6.63	↓	↓	.00715	12.0	16783
21	↓	Br 464	.061	↓	6.63	↓	↓	.00168	24.3	14464
22	↓	Al1100-H	.0625	9 x 6	3.02	↓	.0541	.00420	87	20714
23	↓	↓	.125	↓	↓	↓	↓	.00840	113.5	13512
24	↓	↓	.375	↓	↓	↓	↓	.0252	440	17460
25	↓	Al5052	.125	12 x 12.1	4.93	↓	.11495	.0176	327	18580
1	↓	Cu (hard)	.135	6 x 6	1.77	4.5	.0096	.00220	50.7	23045
2	↓	Cu	.021	7 x 7	1.71	↓	.0142	.000613	11.9	19412
3	↓	Al5052	.125	12.1 x 12	4.93	↓	.0479	.00732	151	20657
4	↓	Cu	.021	5 x 5	1.71	↓	.00590	.000181	3.35	18508
5	↓	Br 464	.026	7 x 7	6.63	↓	.0142	.00020	3.7	18500
6	↓	Br 464	.061	↓	6.63	↓	↓	.00459	7.6	16557
7	↓	Al6061-T6	.032	↓	4.2	↓	↓	.00038	7.5	19737
8	↓	Cu (hard)	.135	4 x 4	1.77	↓	.00318	.000491	12.1	24644

METALLIC SAMPLES (Continued)

Sample No.	Form	Material	Thickness (inches)	Dimensions (inches)	ρ Resistivity ($\mu\Omega$-cm)	R (inches)	$f\left(\frac{a}{2},\frac{b}{2},R\right)$	$F_i(a,b,R)$	H (gamma)	$\frac{H}{F}$
9	Plate	Cu (hard)	.135	4 x 3	1.77	4.5	.00209	.000279	7.1	25448
10	↓	Cu (hard)	.135	4 x 2	1.77	↓	.00110	.000125	1.9	15200
11	↓	Al6061-T6	.032	6 x 6	4.2	↓	.0096	.000220	4.5	20455
12	↓	Br 464	.026	↓	6.63	↓	↓	.000113	2.2	19469
13	↓	↓	.061	↓	↓	↓	↓	.000265	6.7	25283
14	↓	↓	.026	5 x 5	↓	↓	.00590	.000058	1.1	18966
15	↓	Al6061-T6	.032	↓	4.2	↓	↓	.000112	1.5	13393
16	↓	Br 464	.061	↓	6.63	↓	↓	.000136	2.6	19117
17	↓	Al6061-T6	.775	12 x 12.2	4.2	↓	.048	.0535	908	16972
18	↓	Al1100-H	.375	12 x 6	3.02	↓	.0201	.01121	225	20071
19	↓	↓	.125	↓	↓	↓	↓	.00374	43.1	11521
20	↓	↓	.0625	↓	↓	↓	↓	.00187	27.9	14920
21	↓	Br 70-30	.125	↓	6.16	↓	↓	.00183	24.6	13443
22	↓	Br 70-30	.0625	↓	6.16	↓	↓	.000916	12.3	13428
23	↓	Al1100-H	.375	9 x 6	3.02	↓	.01546	.00720	151	20972
24	↓	↓	.125	↓	↓	↓	↓	.00240	32	13333
25	↓	↓	.0625	↓	↓	↓	↓	.00120	22.1	18417

METALLIC SAMPLES (Continued)

Sample No.	Form	Material	Thickness (inches)	Dimensions (inches)	ρ Resistivity ($\mu\Omega$-cm)	R (inches)	$f\left(\frac{a}{2},\frac{b}{2},R\right)$	$F_i(a,b,R)$	H (gamma)	$\frac{H}{F}$
26	Plate	Al1100-H	.375	6 x 6	3.02	4.5	.009597	.00358	86	24022
27			.125					.00119	18.8	15798
28			.0625					.000596	13.2	22000
29		Br 70-30	.125		6.16			.000584	13.1	22432
30			.125					.000584	11.4	19521
31			.0625					.000292	5.9	20206
32			.0625					.000292	5.2	17808
1		Cu (hard)	.135		1.77	6.7	.00324	.000743	14.7	19784
2		Cu	.021	7 x 7	1.71		.00498	.000215	3.85	17907
3		Al5052	.125	12.1 x 12	4.93		.0203	.00310	60.6	19548
4		Cu	.021	6 x 6	1.71		.00324	.000119	25.23	20168
5		Cu	.021	5 x 5	1.71		.00193	.000059	13, 1.0	19492
6		Br 464	.026	7 x 7	6.63		.00498	.000070	13, 1.0	16429
7		Br 464	.061		6.63			.000161	2.5	15528
8		Al6061-T6	.032		4.2			.000133	2.4	18045
9		Cu (hard)	.135	5 x 5	1.77		.00193	.000370	7.9	21351
10		Cu (hard)	.135	4 x 4	1.77		.00101	.000156	3.5	22436

METALLIC SAMPLES (Continued)

Sample No.	Form	Material	Thickness (inches)	Dimensions (inches)	ρ Resistivity ($\mu\Omega$-cm)	R (inches)	$f\left(\frac{a}{2},\frac{b}{2},R\right)$	$F_i(a,b,R)$	H (gamma)	$\frac{H}{F}$
11	Plate	Cu (hard)	.135	4 x 3	1.77	6.7	.000657	.000088	1.9	21542
12				6 x 15			.000339	.000024	.62	25619
13				4 x 2			.000343	.000039	.63	16154
14				6 x 2			.000564	.000057	.95	16550
15		Al6061-T6	.032	6 x 6	4.2		.00324	.000074	1.3	17497
16		Br 464	.026		6.63		.00324	.000038	.70	18325
17		Br 464	.061		6.63		.00324	.000090	1.4	25974
18		Cu	.021	6 x 4	1.71		.00178	.000054	1.1	20408
19		Al6061-T6	.032	6 x 4	4.2		.00178	.000034	.68	20059
20		Br 464	.026	5 x 5	6.63		.00193	.000019	.33	17368
21		Br 464	.061	6 x 4	6.63		.00178	.000041	.68	16667
22		Al6061-T6	.032	5 x 5	4.2		.00193	.000037	.70	19126
23		Br 464	.061	5 x 5	6.63		.00193	.000045	.76	17079
24		Al7075-T6	.250	10.9 x 24.5	5.7		.0327	.01146	173, 178	15314
25		Lead	1.0	3 x 6.2	21		.000948	.000101	1.54	15298
26		Al6061-T6	.775	12 x 12.17	4.2		.0179	.01997	448	22434
27		Al6061-T6	.355	12.13 x 12.05	4.2		.0191	.00980	20.3	20714

METALLIC SAMPLES (Continued)

Sample No.	Form	Material	Thickness (inches)	Dimensions (inches)	ρ Resistivity ($\mu\Omega$-cm)	R (inches)	$f\left(\frac{a}{2},\frac{b}{2},R\right)$	$F_i(a,b,R)$	H (gamma)	$\frac{H}{F}$
28	Foil	Al5005	.002	16 x 28.5	3.3	6.7	.0591	.000399	5.25	13158
29			.002	16 x 18.5			.0439	.000230	3.93	17087
30			.001	13.75 x 18			.0361	.000087	1.02	11724
31			.002	8 x 18.5			.0174	.000070	1.02	14571
32	Plate		.04	6.8 x 8.8			.00046	.000308	5.1	16553
33			.04	12.8 x 16.75			.0310	.000276	4.3	15580
34		Br 70-30	.375	9 x 6	6.16		.00652	.00126	20.7	16429
35			.125					.000421	7.3	17340
36			.0625					.000210	3.5	16667
37		Al1100-H	.375	6 x 6	3.02		.00324	.00121	24.1	19917
38			.125					.000402	6.1	15174
39			.0625					.000201	4.0	19900
40		Br 70-30	.375		6.16			.000691	11.1	18782
41			.125					.000197	3.7	18782
42			.0625					.000099	1.8	18182
43		Al5005-H18	.05	9 x 15	3.3		.0174	.00159	26.4	16604
44		Al3003-H18	.063	3 x 16.5	4.3		.00302	.000078	1.5	19693

METALLIC SAMPLES (Continued)

Sample No.	Form	Material	Thickness (inches)	Dimensions (inches)	ρ Resistivity ($\mu\Omega$-cm)	R (inches)	$f\left(\frac{a}{2},\frac{b}{2},R\right)$	$F_i(a,b,R)$	H (gamma)	$\frac{H}{F}$
45	Plate	Ti 75A	.125	20.65 x 12	60	6.7	.0339	.000677	7.6, 7.7	13258
46		Al 5052-H38	.125	8 x 28	4.93		.0218	.00284	44.2	15563
47		Cu	.030	12 x 12	1.71		.0201	.00212	36.9	17406
48				12 x 12			.0201	.00212	39.3	18538
49				12 x 24			.0374	.00588	79.2	13469
50		Al 6061-T5	.080	21.8 x 6.5	4.2		.0154	.00118	16.0	13559
51		Al 3003-H18	.063	3 x 16.5	4.2		.00301	.000078	1.3	16496
52				3 x 16.5	4.3		.00301	.000078	1.5	19182
53				3 x 14.5			.00276	.000073	1.4	19753
54				3 x 12.5			.00244	.000066	1.2	18127
55				3 x 10.5			.00209	.000059	1.2	20408
56				3 x 8.5			.00168	.000050	1.0	20842
57				3 x 6.5			.00124	.000040	.72	18182
58		Cu	.030	12 x 3	1.71		.00236	.000078	1.3	16195
59				12 x 5			.00567	.000351	4.9, 5.1	14295
60				10 x 5			.00439	.000288	3.9	13542
61				8 x 5			.00340	.000193	3.5	18135

METALLIC SAMPLES (Continued)

Sample No.	Form	Material	Thickness (inches)	Dimensions (inches)	ρ Resistivity ($\mu\Omega$-cm)	R (inches)	$f\left(\frac{a}{2},\frac{b}{2},R\right)$	$F_i(a,b,R)$	H (gamma)	$\frac{H}{F}$
62	Plate	Cu	.030	6 x 5	1.71	6.7	.00235	.000113	2.4	21239
63				4 x 12			.00390	.000182	3.1	17033
64				4 x 10			.00325	.000160	2.5	15625
65				4 x 8			.00254	.000134	1.9	14179
66				4 x 6			.00178	.000078	1.3	16710
67				12 x 24			.0374	.00588	79	13436
68				12 x 12			.0201	.00212	38.5	18160
69				6 x 12			.00760	.000600	9.1	15167
70		Al6061-T6	.0625	20 x 4.75	4.2		.00771	.000338	4.9	14349
71		Cu	.030	12 x 3	1.71		.00236	.000078	1.4	17995
72		Al5005-H18	.05	9 x 15	3.3		.01746	.00159	25.9	16341
73		Al1100-H	.375	12 x 6	3.02		.00760	.00425	68.9	16212
74			.125					.00142	15.5	10916
75			.0625					.000708	10.2	14571
76		Br 70-30	.375		6.16			.00208	28.7	13772
77			.125					.000693	9.8	14141
78			.0625					.000347	4.3	12392

METALLIC SAMPLES (Continued)

Sample No.	Form	Material	Thickness (inches)	Dimensions (inches)	ρ Resistivity ($\mu\Omega$-cm)	R (inches)	$f\left(\frac{a}{2},\frac{b}{2},R\right)$	$F_i(a,b,R)$	H (gamma)	$\frac{H}{F}$
79	Plate	Al1100-H	.375	9 x 6	3.02	6.7	.00552	.00257	50	19455
80	↓	↓	.125	↓	↓	↓	↓	.000857	11.9	13886
81	↓	↓	.0625	↓	↓	↓	↓	.000428	7.8	18224

APPENDIX A

METALLIC SAMPLES

Sample No.	Form	Material	Thickness	Dimensions (inches) OD	Dimensions (inches) ID	ρ Resistivity ($\mu\Omega$-cm)	R (inches)	$g\left(\frac{a}{2},R\right)$	g(a,R)	$F_i(a,b,R)$	H (gamma)	$\frac{H}{F}$
1	Plate	Al 1100-H	.0625	10		3.02	6.7	.0107		.00111	19.4	174.78
2			.125							.00221	28.2	12760
3			.375							.00664	150.6	22681
4			.75							.0133	285	21429
5		Br 70-30	.0625			6.16				.000543	8.6	15838
6			.125							.00109	16.9	15505
7			.375							.00326	5716	17689
8			.75							.00650	107	16462
9	Loop	Al 1100-H	.0625		9.5	3.02			.0634	.000132	2.8	21212
10			.125							.000264	4.2	15909
11			.375							.00079	17.2	21772
12			.75							.00158	31.8	20127
13		Br 70-30	.0625			6.16				.000065	1.2	18462
14			.125							.000129	2.8	21705
15			.375							.000388	7.3	18814
16			.75							.00078	13.8	17692

APPENDIX A

METALLIC SAMPLES

Sample No.	Form	Direction Observed (into)	Material	Dimensions (inches) OD	ID	L	t_{eff} (inches)	$f(a,b,R_1)$	$f(a,b,R_2)$	ρ Resistivity ($\mu\Omega$·cm)	L/R_o	$f_i(a,b,R)$	H (gamma)	$\frac{H}{F}$
1	Tube	Side	Br 464	4.50	4.24	9.4	.1082	.00331	.000947	6.63	6.7	.000422	7.35	17417
2	↓	End	Br 464	4.50	4.24	9.4	.13	.00323	.000966	6.63	↓	.000194	4.4	22680
3	↓	Side	Cu	3.12	3.036	6.8	.0658	.00128	.000490	1.71	↓	.000154	2.5	16234
4	↓	End	Cu	3.12	↓	6.8	.0475	.00146	.000541	1.71	↓	.000085	1.55	18235
5	Rod	Side	Al6061-T6	2.00	↓	2.315	.785	.000153	.000078	4.2	↓	.000047	.89	18936
6	Rod	End	Al6061-T6	2.00	↓	2.315	1.00	.000064	.000078	4.2	↓	.000035	.48	13714
7	Tube	Side	Cu	2.63	2.47	4.075	.1218	.000608	.000218	2.03	↓	.000073	1.19	16301
8	Tube	End	Cu	2.63	↓	4.075	.08	.00108	.000544	2.68	↓	.000065	1.13	17385
9	Rod	Side	Al6061-T6	4.0	↓	12.8	3.14	.00373	.001240	4.2	↓	.00488	83.3	17070
10	Rod	End	Al6061-T6	4.0	↓	12.8	2.00	.000254	.000057	4.2	↓	.000948	20.8	21941
11	Tube	Side	Cu	2.63	↓	4.075	.1218	.00156	.000292	2.03	4.5	.000186	3.9	20968
12	↓	End	↓	2.63	2.97	4.075	.08	.00285	.00115	2.03	↓	.000416	3.0	18634
13	↓	Side	↓	3.12	3.036	6.8	.0658	.00373	.00104	1.71	↓	.000416	7.6	18269
14	↓	End	↓	3.12	3.036	6.8	.0425	.00349	.000991	1.71	↓	.000324	4.5	13889

APPENDIX B

RESISTIVITY OF COMMON ALLOYS

APPENDIX B

RESISTIVITY OF COMMON ALLOYS

O*	H**	Alloy	ρ Resistivity (μΩ-cm)	O*	H**	Alloy	ρ Resistivity (μΩ-cm)
ALUMINUM							
+	+	EC	2.8		+	7039	4.9
+	+	1060	2.8	+	+	5052	4.96
+		1100	2.88	+		195C	4.99
	+	1100	3.01	+		214C	4.99
	+	6101	3.0	+		5454	5.1
+	+	5005	3.3	+		142C	5.15
	+	6063	3.3	+	+	5154	5.3
+	+	5050	3.4	+	+	5086	5.5
+		2014	3.45		+	7079	5.5
+		2024	3.47		+	7178	5.5
+		3003	3.47	+		13C	5.65
+		2017	3.82		+	2219	5.7
+		6061	3.8		+	2017	5.79
+		2219	3.9		+	2024	5.79
+	+	5457	3.9		+	7075	5.76
+		6262	3.9	+		5456	5.9
+	+	3004	4.1	+		5083	5.9
	+	2014	4.31	+		5056	5.94
	+	3003	4.31	+		A132C	5.98
	+	6061	4.32		+	5056	6.39
+		430	4.65	+		380C	7.48
	+	6066	4.7	+		220X	8.31
	+	2011	4.8				
COPPER							
		102	1.71			505	3.59
		104	1.71			220	3.92
		105	1.71			314	4.10
		107	1.71			226	4.31
		110	1.71			405	4.31
		113	1.72			230	4.65
		114	1.72			240	5.39
		116	1.72			422	5.7
		147	1.78			260	6.16
		145	1.91			280	6.16
		150	1.99			365	6.19
		122	2.03			366	6.19
		194	2.54			367	6.19
		210	3.08			368	6.19
		8C50	3.16			385	6.16
		175	3.32			425	6.2

RESISTIVITY OF COMMON ALLOYS (Continued)

O*	H**	Alloy	ρ Resistivity (μΩ-cm)	O*	H**	Alloy	ρ Resistivity (μΩ-cm)
		270	6.38			443	6.90
		370	6.39			444	
		377	6.39			445	
		170	6.98			639	7
		172	6.48			675	7.18
		330	6.63			544	9.07
		332	6.63			510	11.49
		335	6.63			614	12.32
		340	6.63			521	13.3
		342	6.63			524	15.68
		353				619	16.3
		356				638	17.4
		360				706	19.12
		464				6.55	24.6
		465				752	28.8
		466				766	31.4
		467				770	31.4
		485	6.63				

MAGNESIUM

O*	H**	Alloy	ρ Resistivity (μΩ-cm)	O*	H**	Alloy	ρ Resistivity (μΩ-cm)
		HM21A-T8	5.0			AZ31B-F	9.2
		ZE10A-H24	5.2			AZ31B-H24	9.2
		ZK60A-T5	5.7-6.0			AM100A (Cast)	10-15
		KIA-F (Cast)	5.7			AZ91C (Cast)	11-13
		HK31A-H24	6.1			AZ63A (Cast)	11-15
		AZ10A-F	6.4			AZ81A (Cast)	12
		ZH62A-T5 (Cast)	6.5			AZ921A (Cast)	12-14
		HZ32A-T5 (Cast)	6.5			AZ61A-F	12.5
		HM31A-T5	6.6			AZ9-1 (Cast)	13
		EZ33A-T5 (Cast)	7.0			AZ80A-T5	14.5
		HK31A-T6 (Cast)	7.7			LA141A-T7	15.2
		ZK51A-T5 (Cast)	8.4				

MISCELLANEOUS METALS

O*	H**	Alloy	ρ Resistivity (μΩ-cm)	O*	H**	Alloy	ρ Resistivity (μΩ-cm)
		TI-35A	55.9			SS 310	77.8
		TI-50A	55.9				
		TI-.2pd	56.5				
		TI-75A	59.8			Monel K500	62
		TI-BV-116-3AL	153			Inconel 706	100
		TI-6Al-6v-25w	157			Inconel 718	126
		TI-Gal-4v	171				
		TI-5AL-25Sn	181.5			Nitonol 55	52-58
		TI-8AL-1070-lv	198.2			Nitonol 60	52-58

RESISTIVITY OF COMMON ALLOYS (Continued)

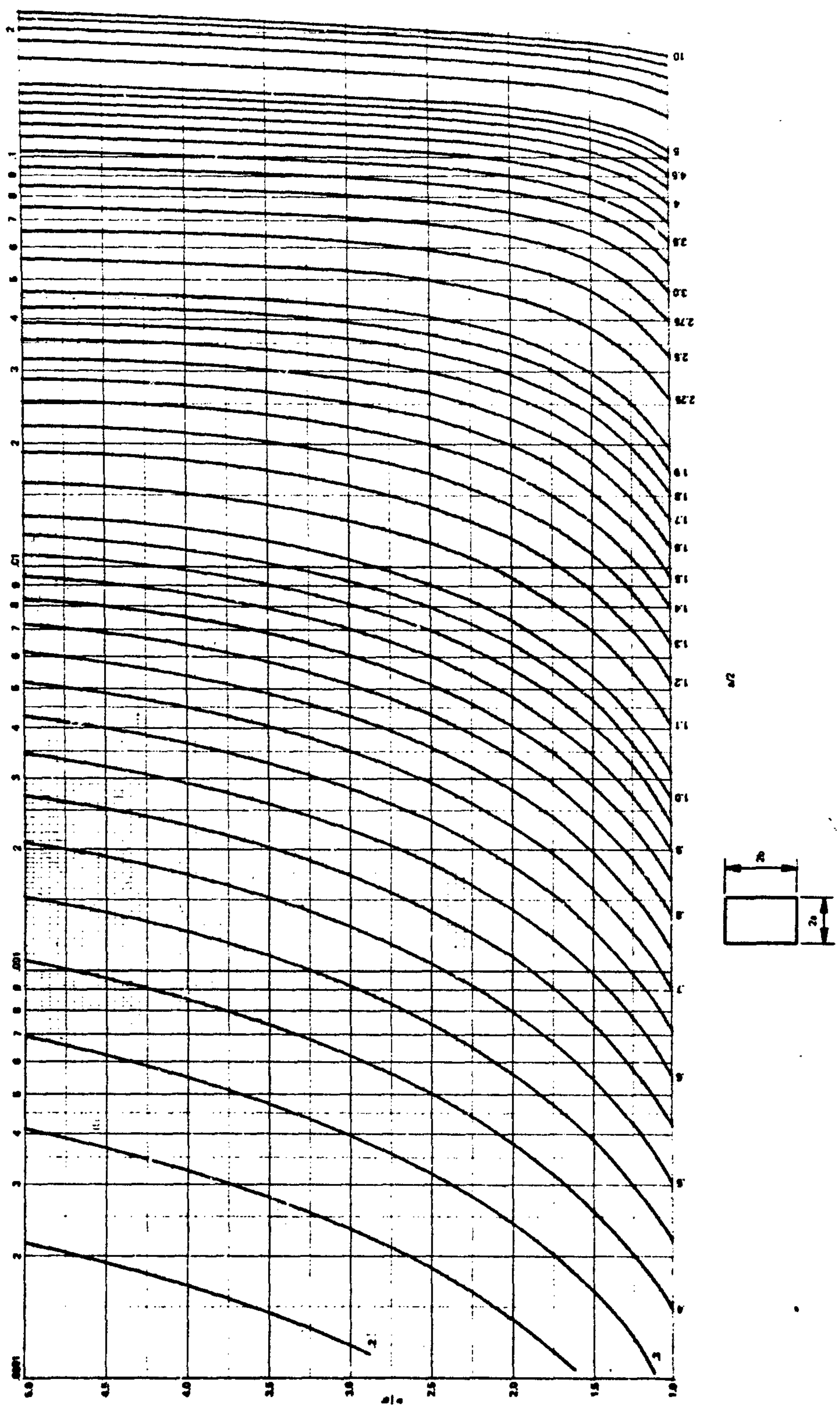
O*	H**	Alloy	ρ Resistivity (μΩ-cm)	O*	H**	Alloy	ρ Resistivity (μΩ-cm)
		Tin	11.0			Tell. Lead	20.6
		60-40 Solder	15.0			Lead	20.6
		5050 Solder	15.5			Ant. Lead	25.3

* O (Annealed)

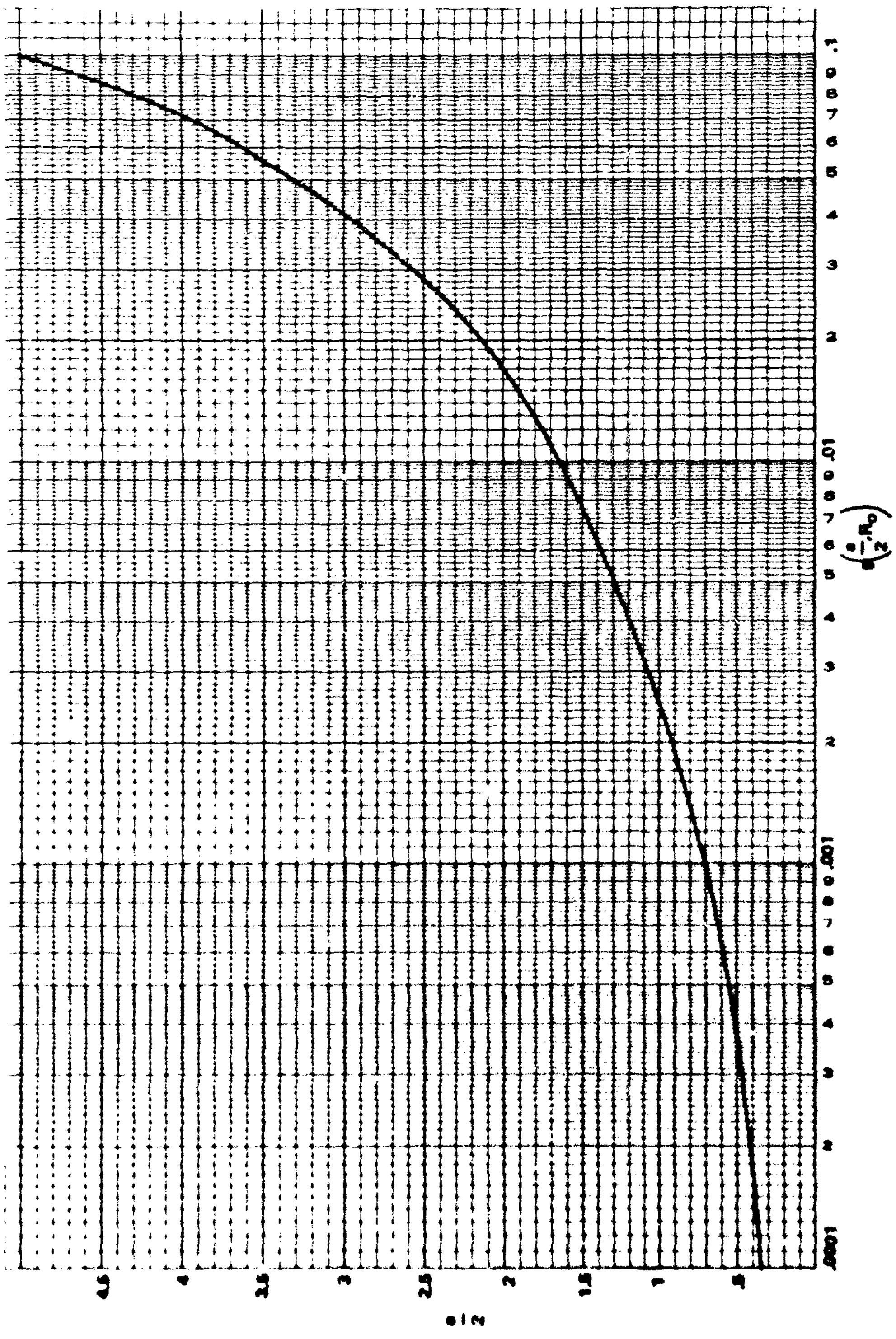
**H (Hardened)

APPENDIX C

RECTANGULAR AND CIRCULAR PLATES



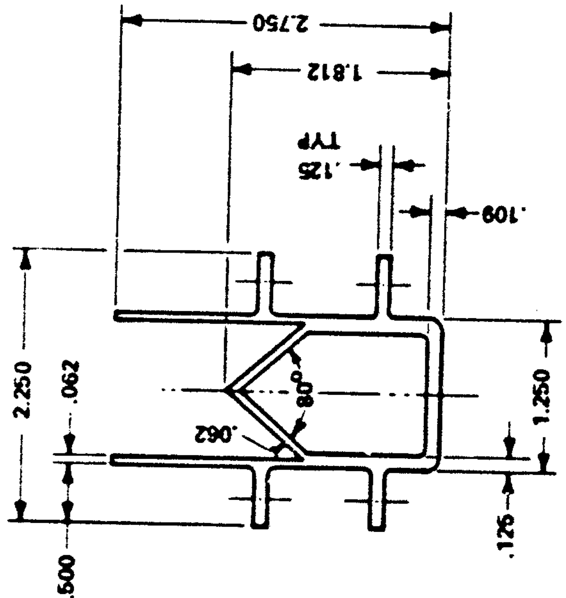
Rectangular Plates



Circular Plates

APPENDIX D

ALUMINUM EXTRUSION DRAWING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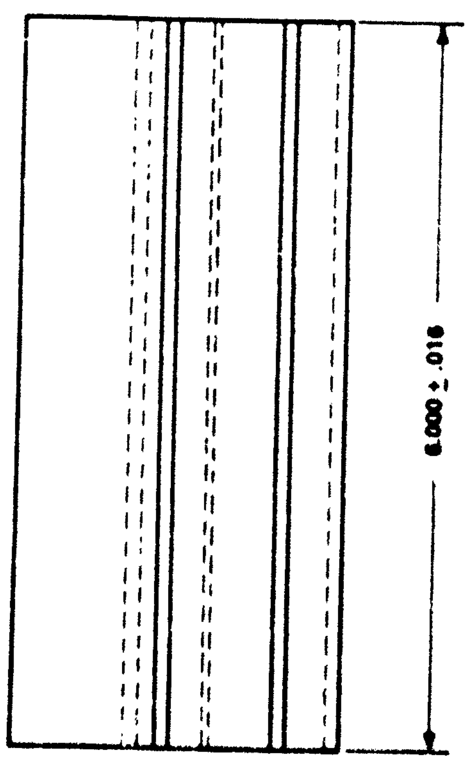
1.812
.125
TYP
.109
2.250
.062
80°
.062
1.250
.125
.500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APPENDIX E

MILITARY SPECIFICATION MIL-M-19595B(OS)

MAGNETIC EFFECT LIMITS FOR NONMAGNETIC
EQUIPMENT USED IN THE PROXIMITY OF
MAGNETIC INFLUENCE ORDNANCE

MIL-M-19595B(OS)

11 January 1971
SUPERSEDING
MIL-M-19595A(Wep)
21 April 1961

MILITARY SPECIFICATION

MAGNETIC EFFECT LIMITS FOR NONMAGNETIC EQUIPMENT USED IN THE PROXIMITY OF MAGNETIC INFLUENCE ORDNANCE

This specification has been approved by the Naval Ordnance Systems Command, Department of the Navy.

1. SCOPE

1.1 Scope. - This specification covers the magnetic effect limits for essentially nonmagnetic equipment used in the proximity of magnetic influence ordnance. This specification covers finished equipment. If it is used for replaceable accessories, components, or raw material intended for use on finished equipment, the special test conditions of 6.2(d) and (e) must be specified. Approval of components or raw materials shall in no case be construed as a guarantee of the acceptance of the finished equipment.

2. APPLICABLE DOCUMENTS

2.1 Not applicable.

FSC 9999

3. REQUIREMENTS

3.1 Preproduction samples. - As soon as possible after the award of the contract or order, the contractor shall submit not less than three preproduction items of each equipment type to the facility specified by the procuring activity (see 6.2c). Items shall be manufactured using the same methods and procedures and at the same plant location to be used for the regular production. These items will be tested as specified in 4.2, herein, and are for the purpose of determining that the production item meets the requirements of this specification.

3.2 Method I - Magnetic effects limits. - The change in flux density of the background magnetic field shall not exceed 0.05 millioersteds (5 gamma) when the equipment is tested in accordance with 4.4.1 and 4.4.2.

3.3 Method II - Eddy current generated field limits. - Eddy current generated field shall not exceed 0.05 millioersteds (5 gamma) when the equipment is tested in accordance with 4.4.3.

3.4 Method III - Total magnetic effects and eddy current generated field. - The total of the magnetic effects, as measured in accordance with 4.4.1 and 4.4.2, and the eddy current generated field, as measured in accordance with 4.4.3 along any axis, shall not exceed 0.05 millioersteds (5 gamma).

3.5 Demagnetization. - All equipment shall be demagnetized after completion of the tests of 4.4, in accordance with 4.5.

3.6 Identification. - After the inspection acceptance of 4.2 and 4.3, the contractor shall permanently and legibly mark, in the presence of the Government inspector, the low mu symbol "μ" on each item of equipment that conforms to the requirements of 3.2, 3.3 and 3.4. A Nitinol stamping

tool shall be used whenever possible; electric etching may be used on hard materials. Equipment that is too small or cannot otherwise be marked shall be tagged or placed in envelopes that are appropriately marked.

4. QUALITY ASSURANCE PROVISIONS

4.1 Responsibility for inspection. - Unless otherwise specified in the contract or purchase order, the supplier is responsible for the performance of all inspection requirements as specified herein. Except as otherwise specified in the contract or order, the supplier may use his own or any other facilities suitable for the performance of the inspection requirements specified herein, unless disapproved by the Government. The Government reserves the right to perform any of the inspections set forth in the specification where such inspections are deemed necessary to assure supplies and services conform to prescribed requirements.

4.2 Preproduction inspection. - The preproduction items shall be examined and tested in accordance with 4.4 to determine compliance with the requirements of 3.2, 3.3 and 3.4. Accepted preproduction items will become the property of the procuring activity and will be included in the quantity of items specified in the contract or order.

4.2.1 Preproductions test results. - When tests are completed on the preproduction items, the inspecting facility shall notify the Government inspector, who in turn shall immediately notify the contractor of the test results and of any specific deficiencies. If any item fails to comply with the requirements of this specification and the contract or order and applicable documents referenced therein, the contractor shall correct the deficiencies and submit additional items until an entire set of satisfactory items has been submitted. These items shall be accompanied by a description of the changes made to correct the faults of the previous submissions. Further production of equipment by the

contractor prior to the approval of the procuring activity or completion of inspections and tests on the preproduction items shall be at the contractor's risk.

4.3 Acceptance inspection. - The equipment and procedure used to measure the magnetic effect in 4.4.1.2 must be approved by the Naval Ordnance Systems Command.

4.3.1 Magnetic effect inspection. - Every item submitted for acceptance shall be tested in accordance with 4.4.1 in order to ascertain compliance with the requirements of 3.2.

4.3.1.1 Rejection and resubmission. - If the magnetic effect of any item exceeds the limit of 3.2, it shall be rejected. The rejected item will be inspected to determine why it failed to pass the limit set forth in 3.2. If the rejected item can be corrected by means other than demagnetization, the item may be resubmitted for acceptance testing. A determination shall be made as to the cause of the increase in the magnetic effect from that of the preproduction samples, and the production process shall be corrected to eliminate this increase.

4.3.2 Inspection of the magnetic effect of electric circuits. - Every item submitted for acceptance shall be tested in accordance with 4.4.2 in order to ascertain compliance with the requirements of 3.2.

4.3.2.1 Rejection and resubmission. - If the magnetic effect of any item exceeds the limit of 3.2, it shall be rejected. The rejected item will be inspected to determine why it failed to pass the limit set forth in 3.2. If the rejected item can be corrected, the item may be resubmitted for acceptance testing. A determination shall be made as to the cause of the increase in the magnetic effect from that of the preproduction samples, and the production process shall be corrected to eliminate this increase.

4.3.3 Eddy current generated field inspection. - Every item submitted for acceptance shall be tested for eddy current generated field in accordance with 4.4.3 in order to ascertain compliance with the requirements of 3.3.

4.3.3.1 Rejection and resubmission. - If the eddy current generated field of any item exceeds the limit of 3.3, it shall be rejected. Rejected items, after correction of defects, may be resubmitted for acceptance. A determination shall be made as to why there was an increase in the eddy current generated field from that of the preproduction samples, and the production process shall be corrected to eliminate this increase.

4.4 Test procedures.

4.4.1 Magnetic effect test. - Each item shall be idealized as in 4.4.1.1 and then measured for magnetic effect as in 4.4.1.2. The procedure of 4.4.1.1 and 4.4.1.2 shall be sequentially followed for each of the three reference axes selected as in 4.4.1.4. The magnetic effect of the item is the largest of the three measurements.

4.4.1.1 Magnetic idealization. - Idealization shall consist of placing each item in a uniform magnetic field of five oersteds, with the reference axis aligned parallel to the field, and of superimposing a cycled pulsed magnetic field parallel to the uniform constant background field. A cycle shall consist of a square positive pulse of minimum duration of one second, a minimum of one off, a square negative pulse of equal amplitude and of minimum duration of one second, and finally a minimum of one second off. The amplitude of the positive pulse of the first cycle shall be between forty and sixty oersteds at the start. The pulse amplitude shall be reduced between successive cycles by a maximum of two oersteds. The cycling shall continue until the amplitude is reduced to zero.

4.4.1.2 Magnetic effect measurement. - Unless otherwise specified, the detection point (the center of the active element in the magnetometer sensor) for each magnetic effect measurement shall be 4-1/2 ± 1/4 inches from the surface of the item. The detection sensor shall be aligned parallel to the background field. At the start of the measurement, the item shall have its reference axis aligned parallel to the background magnetic field and passing through the point at which the magnetic field change is measured. The initial distance between the item and detection point shall be at least two feet. The item is then brought to 4-1/2 inches from the detection point. It is next rotated 360° about an axis perpendicular to the reference axis, in such a manner so that the closest point of the item to the detection point is kept at 4-1/2 inches throughout the entire rotation. After completing the 360° rotation, the item is removed to the point. The magnetic effect measured for a given axis is the maximum variation of the magnetic field at the detection point during this motion. (i.e., The magnetic effect is the sum of the absolute values of the largest plus and minus variations as measured during the test.)

4.4.1.3 Standard test temperature and background magnetic field limit. - Magnetic effect measurements shall be performed at a temperature of 80 ± 20°F and in a minimum background magnetic field of 450 millioersteds. (The background field level is measured when the test object and all other magnetic materials are removed from the vicinity of the detection point.)

4.4.1.4 Selection of reference axes. - Three mutually perpendicular reference axes shall be selected for each equipment type. In general, one reference axis shall be the longest axis of the equipment type, and another reference axis shall be the longest axis perpendicular to the preceding axis.

4.4.2 Test for magnetic effect of electric circuits. - If the equipment has electric circuits, its magnetic effects shall be measured with each circuit on and with each possible combination of two or more circuits on as per 4.4.1.2. The same reference axes selected in 4.4.1.4 shall be used for the measurements. The equipment shall be demagnetized as per 4.5 before this test. The magnetic effect of electric circuits is the largest magnetic effect measured.

4.4.2.1 Electric circuit test conditions. - The maximum rated operating voltages shall be applied, and where applicable, fresh batteries shall be used for these tests. All controls shall be adjusted for maximum current flow.

4.4.2.2 Standard test temperature and background magnetic field limit. - Magnetic effect measurements shall be performed at a temperature of 80 ± 20°F and in a minimum background magnetic field of 450 millioersteds. (The background field level is measured when the test object and all other magnetic materials are removed from the vicinity of the detection point.)

4.4.3 Eddy current generated field test. - Each item shall be measured for eddy current generated field as in 4.4.3.1. The procedure of 4.4.3.1 shall be sequentially followed for each of the three reference axes selected as in 4.4.1.4. The item shall be demagnetized as per 4.5 before this test. The eddy current generated field of the item is the largest of the three measurements.

4.4.3.1 Eddy current generated field measurement. - Unless otherwise specified, the detection point (the center of the active element in the magnetometer sensor) for each eddy current generated field measurement shall be 4-1/2 ± 1/4 inches from the surface of the item. The detector sensor shall be aligned perpendicular to the background field. At the start of the measurement, the item shall have its reference axis aligned perpendicular to the background field and passing through the point at which the eddy current

generated field is measured. The initial distance between the item and the detection point shall be at least two feet. The item is then brought to 4-1/2 inches from the detection point. It is then moved in a rocking or nutational motion about the center of the reference axis so that one end of the item moves toward the detector while the other end moves away from the detector. The movement will be through an angle of 30°, 15° in each direction from the original position of the item at the detection point. The rate of movement will be such that 15 complete rocking or nutational motions occur in 10 seconds. (Rate of movement is equivalent to 15 RPM.) After completing the rocking or nutational movements, the item is removed to the starting point. The eddy current generated field measured for a given axis is the maximum variation of the magnetic field at the detection point during this motion. (i.e., The eddy current generated field is the sum of the absolute values of the largest plus and minus variations as measured during the test.)

4.4.3.2 Standard test temperature and background magnetic field limit. - Eddy current generated field measurements shall be performed at a temperature of 80 ± 20°F and is a minimum background field of 450 millioersteds. (The background field level is measured when the test object and all other magnetic materials are removed from the vicinity of the detection point.)

4.5 Demagnetization. - Demagnetization shall consist of passing each item through more than a one hundred oersted peak alternating magnetic field, to a point sufficiently removed where the ambient field is less than one oersted. The motion shall be slow relative to the alternating frequency (several seconds at sixty hertz). The alternating frequency shall be sixty hertz or less. An alternate demagnetization procedure is to slowly reduce to zero the amplitude of the alternating field with the object not moving. No test for demagnetization is required.

4.6 Identification. - The Government inspector shall assure that each item of equipment is properly and correctly identified in conformance to 3.6.

5. PREPARATION FOR DELIVERY

5.1 Not applicable.

6. NOTES

6.1 Intended use. - Items covered by this specification are intended for use in the proximity of magnetic influence ordnance and such ordnance must be insensitive to them. Examples of such items are nonmagnetic tools and equipment used by the Navy in explosive ordnance disposal. These items are not intended for common usage where normal commercial products will suffice.

6.2 Ordering data. - The procuring activity shall specify the following:

a. Title and number of this specification
b. Quantity of preproduction items, if other than three (see 3.1)
c. Facility to perform the inspection (see 3.1, 4.4.1 and 4.4.2)
d. Special test distance if the tested item is not a complete item (see 1.1) (Two inches for replacement items unless otherwise specified)
e. Dimensions of material tested if this specification is used for ordering raw material (see 1.1)

6.3 Preparer. - This specification has been prepared by the Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland for the Naval Ordnance Systems Command, Department of the Navy.

Preparing Activity:
Navy - OS
Proj. No. 9999-N002

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APPENDIX F
TABLE OF SYMBOLS

TABLE OF SYMBOLS

a	One-half width of rectangular plate, inches
b	One-half length of rectangular plate, inches
C^2	Speed of light squared
ϵ_o	Permittiuity constant
ρ	Resistivity, microhm-cm
t	Thickness of sample, inches
π	3.1415
dl	Differential length along a path of integration
H	Magnetic field strength, gamma
H_o	Reference magnetic field strength, gamma
I	Current, amps
A_l	Cross-sectional area of current carrying element, $(\text{inches})^2$
L	Length of perimeter of loop, inches
E	EMF, volts
R	Perpendicular distance from center of sample to point of interest, inches
r	Distance from current path to point of interest, inches
K_o, K_1, K_2, K_3, K_4	Constants
Θ	Angular between normal to center of sample and line connecting center of sample to the sensor
ϕ_H	Magnetic field strength flux
$\mathbf{R}$	Resistance, Ohms
$F_1(a,b,R)$	Configuration function which can be equal to any of the following:

$$\left(\frac{a+b}{2}\right)\left(\frac{t}{\rho}\right)f\left(\frac{a}{2},\frac{b}{2},R\right);\ a\left(\frac{t}{\rho}\right)g\left(\frac{a}{2},R\right);\ \left(\frac{a+b}{2}\right)\left(\frac{t_{eff}}{\rho}\right)\left[\frac{f\left(\frac{a}{2},\frac{b}{2},R_1\right)+f\left(\frac{a}{2},\frac{b}{2},R_2\right)}{2}\right];$$

$$\frac{at_{eff}}{\rho}\left[\frac{g\left(\frac{a}{2},R_1\right)+g\left(\frac{a}{2},R_2\right)}{2}\right];\ \left(\frac{at_{eff}}{2\rho}\right)\left[\frac{g(a,R_1)+g(a,R_2)}{2}\right]$$

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11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY

13. ABSTRACT

Using a simple theoretical approach, a method has been formulated to determine the eddy current-induced magnetic fields (ECI magnetic fields) produced by metallic objects moved in the Earth's magnetic field. The method permits the calculation of the ECI magnetic field of objects having simple shapes and, with a little ingenuity, can be readily extended to more complex shapes. The basic theory establishes criteria by which materials can be selected and designs evaluated to yield a minimum ECI magnetic field.

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2. Magnetic Fields						
3. Explosive Ordnance Disposal						
4. Tools						
5. Design						